Detecting Damage Using Electric Field Measurements: A Computational Sensitivity Study

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14. ABSTRACT

The objective of the Underwater Hull Analysis Model project was to develop a computational condition-based assessment tool to determine the condition of hull. The model would be an advancement in the state-of-the-art for corrosion and coatings damage assessment allowing for evaluation of hull condition based on sensor data in real or near real time. The computational tool was planned to be validated using both experimental and real ship data. An initial stage in the validation process is to determine the relationship between changes in defined boundary conditions and calculated field values. This information is a key component in the capability to identify changes in hull coating damage from changes in measured field values. The work presented is computational in nature. Damage on the order of what is possible to duplicate in physical scale model experiments is added to a known quality of damage. Variations in key calculated parameters are determined, and implications for the creation of the assessment tool are noted. This work provides information on the relationship between incremental damage change and measurable field differences.

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EXECUTIVE SUMMARY

The objective of the Underwater Hull Analysis Model project was to develop a computational condition based assessment tool to determine the condition of hull. The model would be an advancement in the state of the art for corrosion and coatings damage assessment allowing for evaluation of hull condition based on sensor data in real or near real time. The intent was to be able to estimate damage location and size prior to port arrival which would assist in maintenance planning. The computational tool was planned to be validated using both experimental and real ship data. An initial stage in the validation process is to determine the relationship between changes in defined boundary conditions and calculated field values. This information is a key component in the capability to identify changes in hull coating damage from changes in measured field values. The work presented is computational in nature. Damage, on the order of what is possible to duplicate in physical scale model experiments, is added to a known quality of damage.   Variations in key calculated parameters are determined and implications for the creation of the assessment tool are noted. This works provides information on the relationship between incremental damage change and measurable field differences.

1   INTRODUCTION

The Underwater Hull Analysis program involved the development and adaption of computational tools for condition based maintenance (CBM). The objective was to be able to correctly predict changes in hull condition by identifying regions of coating damage in real or near real time. A specific platform was to be identified for the demonstration of the developed tools. After the successful demonstration, these computational tools could then be applied to other platforms. The Future Naval Capabilities (FNC) product was to be a computational tool for incorporation into future impressed current cathodic protection (ICCP) software/systems and for use by the Naval Sea Systems Command (NAVSEA), the In Service Engineering Activity (ISEA), and maintenance planners. Product characteristics of note are:

- Robustness: Complimentary analysis program which utilizes ICCP data output to provide spatial and operational assessment of hull corrosion condition.

- Compatibility: Across computer platform and across ship class

Product features for the underwater hull condition analysis model included the following:

- Hull Potential Map: Analysis model provides hull map of protection potential distribution to highlight problem areas.

- Current Sink Identification: Utilizes sensor directionality matrix to identify and quantify location and magnitude of damaged coating areas (cathodes) locations.

- Composite Hull Condition Assessment: Utilizes ICCP output and reference cell/anode current data for real/near-real time assessment of hull condition and damage assessment.

- Change Identification Map: Denotes and identifies changes in ICCP system spatial configuration allowing for evaluation of impact of payloads, attachments, and appendages.

- Feedback for Control Systems: Time based identification/changes of significant cathodes (sinks) and sources depending on hull condition, payload, and system operation.

The program was originally planned to last for 5 years starting in FY11 with transition of the technology to PMS450 in FY15. At the end of FY15 the product would be at a technical readiness level (TRL) of 6. At this level, the product would have been demonstrated in a relevant environment with limited documentation available. Early termination of the program did not allow for complete development of the planned computational tools. Validation of computational work, such as the model developed of the targeted demonstration platform, would be critical components of the progress from concept to achieving a TRL 6.   The work

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documented in this report represents the initial steps in the computational based tool validation process.

The work presented is a proof of concept that observable variations in off-board field measurements are associated with small changes in hull damage, such as are feasible to represent on physical scale model hull geometries. The relationship between off-board electric potential differential characteristics and hull damage is not linear in nature and further complicated by measured and calculated errors. It is recognized that any change in boundary conditions, such as the addition of exposed metal on the hull, will result in variations in the solution. However, both experimental and computational methods introduce errors in measurement through minimum feature size and measured value limitations. These errors could easily result in one set of measured field data mapping into multiple damage patterns. This computational study provides insight into the degree of change in off-board field characterization that can be expected from small increments in hull damage.

2 VALIDATION

The computational study presented in this report is not in itself validation, but it is part of the validation process. Therefore it is important to understand what is meant by computational tool validation. Validation specifically addresses comparing computational results with real world values; but is only one component of the qualification, verification and validation (QV&V) process. Even though it is common to refer to a validated computational tool, it is actually the entire QV&V process that provides confidence that the computational tool correctly predicts real world response.

QV&V is a process and requires all three components. Qualification means the correct governing equations have been defined to capture observed behavior. Verification means that the solution processes for the algorithms used are mathematically correct. Validation means that real data (either from structure or experiment) matches with a given tolerance the simulated data. Validation is useless unless qualification and verification are completed. Verification only can easily result in 'garbage in, garbage out' since all that is known of a verified computational solution is the math in the solution process is correct. Without qualification, the risk of 'garbage in, garbage out' is equally high. One example of incorrect results would be if a correctly calculated static solution was used for a dynamic transient problem. Without qualification we would not know that the problem as defined is incorrect.

Another way to understand the QV&V triad is to consider the different representations one can create for any system. Any system will have physical, conceptual, and computational representations. The physical representation of a system is the structure (the real world). The conceptual representation of a system is the mathematics representing the physics of the system (the analytical model). The computational representation is the collection of all of those things that make up a computational model including the mesh, material definitions, loadings, and

boundary conditions (the computer model). When the behavior simulated by the computational representation is identical to the behavior of the physical system, the computational system is said to be "validated." When the behavior simulated by the conceptual aspect is identical to the one simulated by the computational system then it is said that the conceptual (equations) and computational (algorithm, code, and visualization) aspects are "verified."

What is considered the 'real world' can change based on the objective of the analysis. When experimental data is generated for comparison with computational or conceptual results, the system that represents reality is the test specimen and experimental set up. In the case of comparisons with physical scale modeling results, the real world is represented by the scaled ship model. Simplifications made in ship appendages or systems that are required due to the geometric scale of the model are no longer considered simplifications. When the computational model is created, it is defined to match the scaled ship model as exactly as possible. Differences with real ship geometries and systems are not important at this phase of the validation process.

The computational code used in this work is BEASY-CP, a commercial boundary element code [1]. It has been verified by the code developer for a wide range of problems including the steady state solution of electrochemical potential in a uniform finite volume electrolyte. The solution for the electrochemical potential incorporated into the commercial code used has been shown to be qualified for the solution of electrical fields generated on-board and off-board [2,3].

Validation is itself a process. This report addresses only one of the initial steps in the process. Specifically, this report determines the relationship between changes in defined boundary conditions and calculated field values. Understanding this relationship is a key component in developing the capability to identify changes in hull coating damage from changes in measured field values. The work presented is computational in nature. Damage on the order of what is possible to duplicate in physical scale model experiments is added to a known quality of damage. Variations in key calculated parameters are determined and implications for the creation of the assessment tool are noted.

3 IMPRESSED CURRENT CATHODIC PROTECTION (ICCP) SYSTEMS

The problem considered is the electrical fields generated by a shipboard Impressed Current Cathodic Protection (ICCP) system. In this section, the authors will define the governing equations appropriate for exterior surfaces under steady state conditions. A shipboard ICCP system has three basic components: 1) reference cells that are Ag/AgCl based, 2) controller and power supply, and 3) anodes. Shipboard ICCP systems are typically designed with several reference cells to monitor potential levels at critical locations on the hull providing feedback to the controller to regulate output current to the anodes. In this way, the ICCP maintains the set potential levels for operation. ICCP systems can have complex digital control systems. The ICCP system also naturally compensates for most environmental factors, which influence the

cathodic current demand behavior, by continually regulating the anode current output to maintain the hull polarization to the designated set potential. The set potential is typically defined between −800 and −850 mV verses the Ag/AgCl reference cell. This is sufficient to protect steel structures. For this damage sensitivity study the ICCP on the computational model starts with a simple feedback control.

3.1   EVALUATION OF ICCP SYSTEM GENERATED FIELDS

Mathematically the hull and ICCP system are combined into a single system surrounded by seawater. The wetted portion of the hull is included in this system. For surface ships, this means the hull below the waterline. For submarines, this means the entire hull. Even though seawater is a multi-component solution, it is also considered to be uniformly mixed and represented by a single conductivity value. Since we are solving for the exterior hull and off-board fields, crevices and other confined spaces in which this assumption of uniform mixing would break down are not included in the computational model. The governing differential equation that defines electrochemical generated fields for a structure surrounded by a uniform electrolyte is:

$$k\nabla^2\Phi=0 \tag{1}$$

Φ is the electric potential and k is the conductivity of the electrolyte. Eqn. (1) is commonly referred to as Laplace's equation. For Laplace's equation to be valid the volume surrounding the structure cannot contain either electrical sources or sinks and the total current in must equal the total current out of the system. Anodes and cathodes are defined by application of boundary conditions so these restrictions are not violated. The equation models steady state conditions and does not address corrosion initiation.

The solution space for the problem is the surface, Γ, which bounds the domain, Ω, and is defined as:

$$\Gamma=\Gamma_A+\Gamma_C+\Gamma_I \tag{2}$$

The surface is divided into anodic regions, Γ_A, cathodic regions, Γ_C, and insulated regions, Γ_I. Each region represents a specific component of the ICCP system and ship hull. Anodic regions are the ICCP system anodes and are defined as either a constant current source, q_A, or as a constant voltage source, Φ_A:

$$\partial\Phi(x,y)/\partial n_{(x,y)}=q_A \tag{3}$$

$$\Phi(x,y)=\Phi_A \tag{4}$$

$\Phi(x,y)$ is the electrical potential at the point (x,y) and $n_{(x,y)}$ is the surface normal vector at the point. An individual computer solution defines steady state conditions at a specific point in time at a specific anode current level.

The electric flux at a point on the surface of the cathodic region is defined by;

$$\partial\Phi(x,y)/\partial n_{(x,y)} = f_c \tag{5}$$

where f_c is the cathodic polarization function. The polarization function is experimentally determined and is typically non-linear. In this report, polarization response is modeled as piece-wise linear through using a look-up table format. In general, the value of the potential can be determined if the value of current is defined.

At insulated surfaces, such as painted surfaces, the flux (current density) is constant through time and equal to zero:

$$\partial\Phi(x,y)/\partial n_{(x,y)} = 0 \tag{6}$$

Eqns. (1) through (6) are combined to solve for potential and flux (current density) at all points on the defined surface. The boundary element method through application of a commercial boundary element code is used to obtain solutions for specific boundary value problems.

ICCP systems are defined using a combination of defining specific input values and tracking output solution results. Anodes are defined by assigning specific current values to elements. Current and potential for the cathodes is calculated as part of the solution process based on size and location of the exposed cathodic surfaces and their associated polarization behavior. Reference cell potential values are the solution value of potential at the nodes that are collocated with the reference electrode placement. Reference electrode values are determined in the solution process and are not predefined nodal values. Based on the reference electrode value, the current values at anodes are adjusted and the solution is recalculated. This iterative loop is continued until the reference electrode value is in the target value range. In summary, a valid solution must meet the following two criteria:

(1) The reference electrode values are within the target value range for the given current values;

(2) Total current to anodes associated with a single power supply is less than the power rating of that power supply.

3.2 MATERIAL PROPERTIES

There are two basic material characterizations required for evaluation of ICCP systems: the conductivity of seawater and the polarization response for materials of interest. In this work, full strength seawater is assigned a resistivity of 18.5 ohm-cm; this represents average sea conditions.

Previous work has determined that the accuracy of the boundary element solution is directly related to the appropriateness of the material polarization response chosen. This conclusion is based on the results of multiple analyses. Early work that identified the need for accurate material representations includes that by DeGiorgi, Kee, and Thomas [4]. The ideal situation

would be to duplicate the service conditions in the tests used for determining polarization response. This is impractical so engineering judgment is used to determine the best fit between service and material characterization test conditions. There are two distinct material definitions are used in the present work: perfect paint and steel. Prefect paint is defined as a perfectly insulating surface (a zero current density boundary condition). The steel is defined with a nonlinear polarization response. The responses for steel were experimentally determined in a previous project [5].

4   DAMAGE SENSITIVITY ANALYSIS

The sensitivity study conducted was designed to evaluate the variation in off-board characteristics, a measurable value, due to changes in hull damage. This information is required to determine if the concept of the Underwater Hull Analysis Model is feasible. Feasible implies the ability to produce values against which the model can be validated using experimentally obtained data. Changes made on the hull must result in changes that would be measureable in the off-board fields. While a true minimum damage increment to result in observable change is not determined, response trends are identified. Any true minimum damage increment would be physical scale model geometry and instrumentation sensitivity limited. The sensitivity study is computational.

An isolated area of damage will result in an observed spike in the off-board field as it pairs with other damage to create a dipole. In the absence of other damage, it will be a single point draw from the anodes, resulting in a readily observable spike. Of more usefulness in determining the sensitivity of the approach is the addition of damage to an already existing damaged area on the hull. This approach will not result in an immediately noticeable spike in the off-board field. Changes in off-board field characteristics will be more subtle and give a clearer picture of how much change in damage is required to produce a measurable change in off-board field characteristics.

The approach taken is to evaluate different damage states for a generic underwater hull model with a simple ICCP system using the boundary element code BEASY-CP. BEASY-CP was chosen because of the familiarity with the code. It has been used successfully to model multiple ship hulls and ICCP systems. Damage states identified for the sensitivity study are given in Table 4-1. The baseline damage, damage case 1, is 5.7%. The percent damage is increased to 8.3% for case 2 and 10.7% for case 3. For this feasibility study these percentages are slightly higher than typical but less than the maximum amount of damage [6]. A future study was intended to investigate smaller damage percentages using a more realistic model, that was built in parallel with this work, with distributed damage along the hull and a bare propeller. This study would also incorporate physical scale model measuring attributes such as the accuracy of measured data and how small an area can be represented on the physical scale model.

Table 4-1: Damage States

| Case	Amount of Damage (cm²)	Percent Damage
1: Baseline	127.65	5.7 %
2: Baseline + 2.6%	185.04	8.3 %
3: Baseline + 5%	238.15	10.7 %

5 GENERIC UNDERWATER HULL MODEL

A generic model of a submarine type structure with a disk propeller but without any other appendages was created using the commercial boundary element program BEASY-CP. The model is created on a 1/40th scale and placed into a cylindrical tank as seen in Figure 5−1. The tank modeled is the 914.4 cm diameter tank at the Cathodic Protection Physical Scale Model Facility (CPPSMF) at the Naval Research Laboratory Center for Corrosion Science and Engineering (NRL-CCSE) in Key West, FL. The tank is modeled with a seawater depth of 265.43 cm. The conductivity of the scaled seawater is 135 S/cm, which is a resistivity of 740 ohm-cm. This is equivalent to a full strength seawater conductivity of 0.054 S/cm, which is a resistivity of 18.5 ohm-cm.

The scaled submarine model measures 188.7 cm long with a diameter of 27.8 cm. The submarine lies at a depth of 75 cm. The submarine has a pair of forward anodes (port and starboard) and a pair of aft anodes (port and starboard). The starboard anodes are shown in Figure 5−2. One cathode is placed on the top centerline toward the rear of the submarine. The cathode is modeled as steel and shown in Figure 5−3. The size of the cathode is varied to represent different amounts of damage ranging between typical and maximum states [7]. The exact size of the cathode is mandated by mesh refinement and element size. In case 1, the baseline, the cathode has 5.7% damage. For case 2, the damage is increase by 2.6% to be 8.3% and for case 3, the percent damage is 10.7%, an increase of 2.4% from case 2 or 5% from case 1. The rest of the hull, including the propeller, is defined as insulated. It is important to remind the reader that the geometry presented is representative of a submarine, and is not a scaled version of any existing ship or boat. ICCP system design and other features are defined to represent a functional underwater hull.
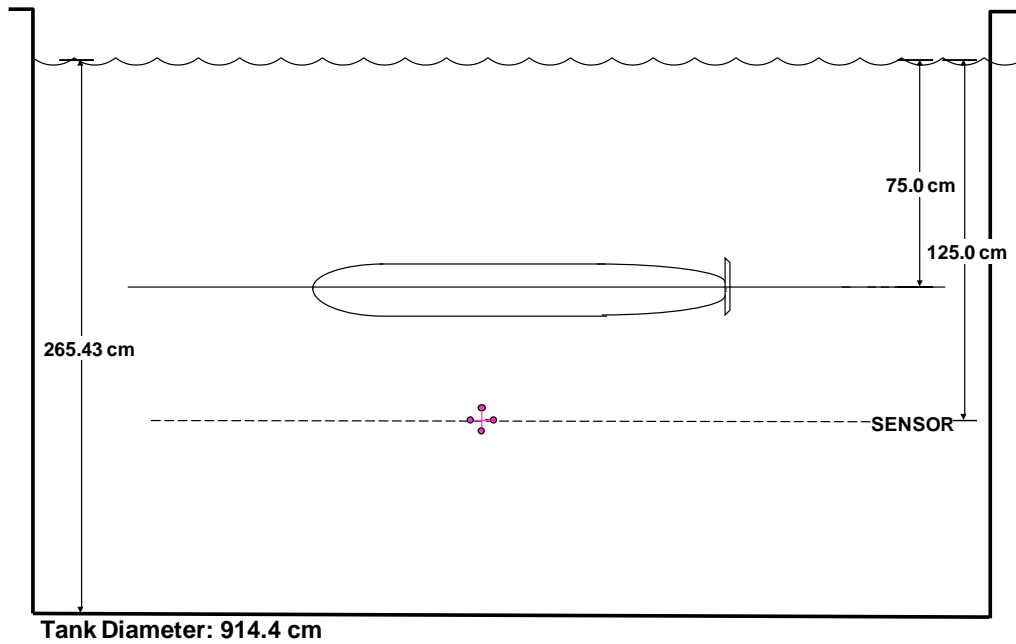
Figure 5-1: Schematic of the submarine and surrounding water tank.
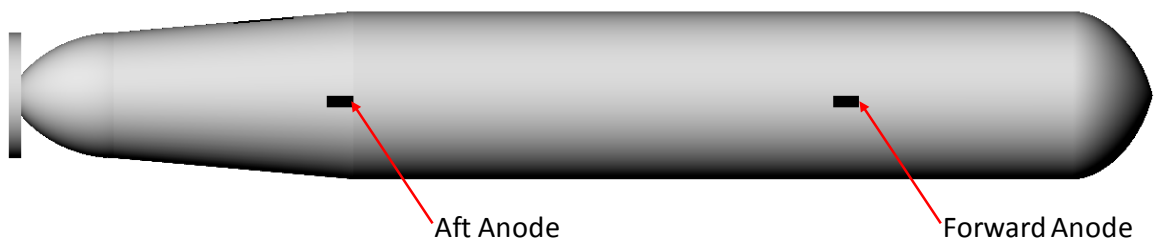
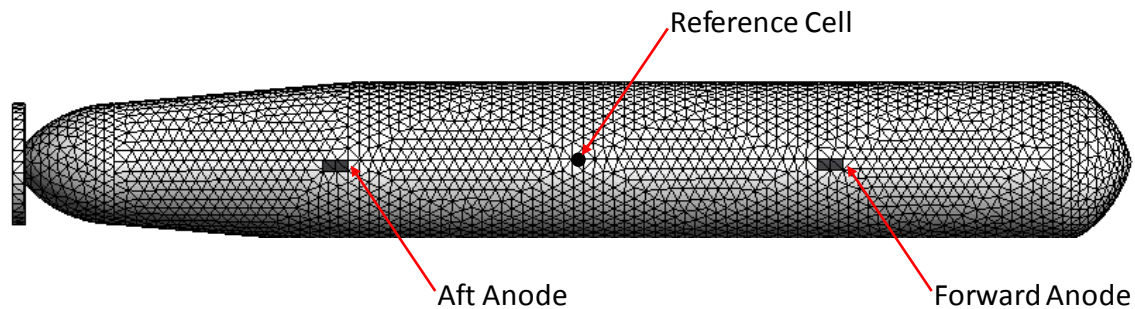**Figure 5-2: Starboard view of submarine showing the location of anodes.**
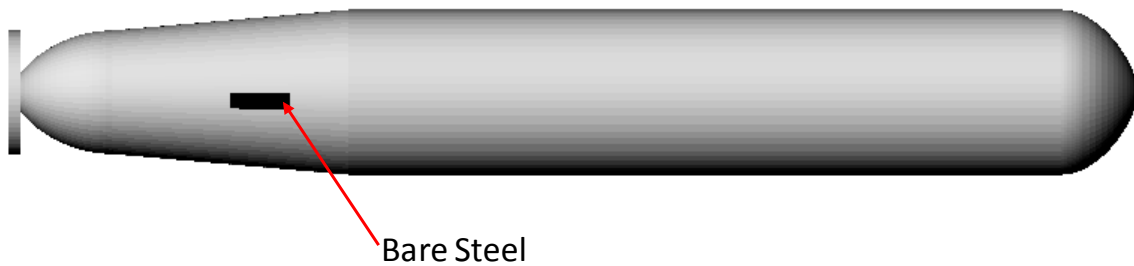
Figure 5-3: Top view of the submarine showing the location of bare steel.
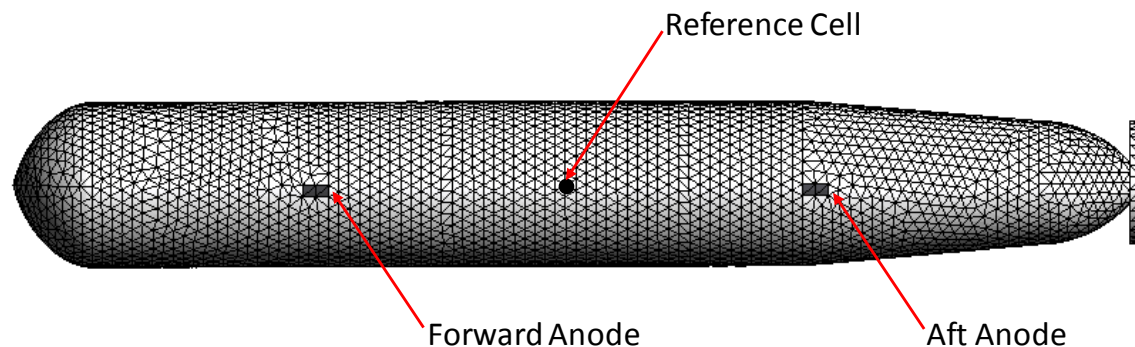
5.1 BOUNDARY ELEMENT MODEL

A total of 10,441 triangular boundary elements were used to mesh both the submarine and the tank walls. Figures 5–4 and 5–5 show the boundary element mesh of triangles used on the hull, while Figure 5–6 shows the boundary element mesh of triangles used on the tank walls. The elements used are six-noded linear elements. The surface of the water is not meshed, but is instead assigned a symmetry boundary condition. This is a standard process in the boundary element problem formulation. The walls and bottom of the tank are defined as insulated surfaces. All analyses were completed on desktop PC with individual runs typically taking 50 minutes.

Reference cells are located approximately half way between the anodes. The reference cell is manually chosen from within the BEASY program by identifying node points. The exact location of the reference point upon the hull surface depends upon the mesh density. The starboard reference cell is shown in Figure 5–4. The port reference cell, as seen in Figure 5–5, is located slightly aft (0.98 cm) of the starboard reference cell and slightly higher (0.004 cm).

Figure 5-4: Starboard side of the submarine showing its triangular surface elements.

Figure 5-5: Port side of the submarine showing its triangular surface elements.
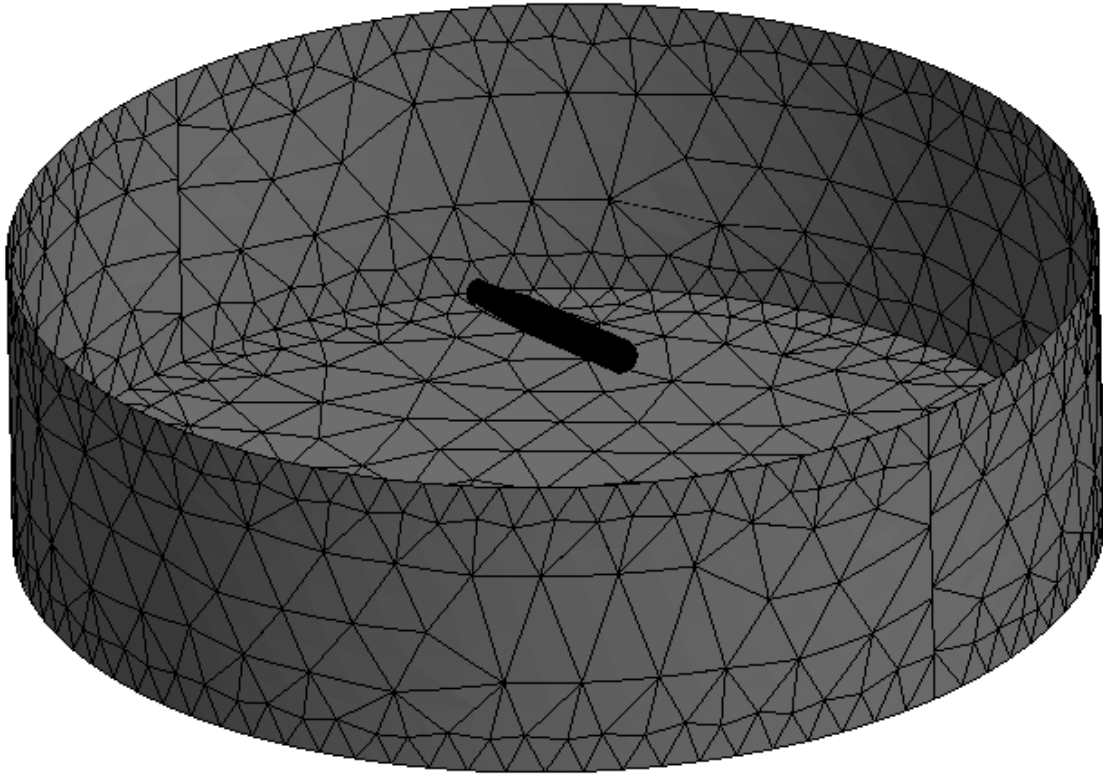
Figure 5-6: The boundary element mesh for the submarine and the water tank.

5.2 OFF-BOARD FIELDS

Computationally, off-board fields are determined from the solution obtained at internal points. Internal points are not connected to the boundary element mesh but are locations internal to the domain defined by the boundary element mesh. The values at internal points are calculated by the computational code interpolating the results from the boundary element mesh to the internal points. The analyst has to define the location of internal points prior to solving; the program calculates the values in a separate step after a valid solution is achieved. To compute the off-board field, a string of internal points is placed along the path where an experimental or an actual range sensor would be located relative to the ship.

A typical sensor used consists of four individual sensors configured as shown in Figure 5–7. For this model a sensor depth of 125 cm was used. The sensor path runs under the boat's centerline. In the computational model lines of internal points are placed along the path where the tips of the individual sensors would travel.
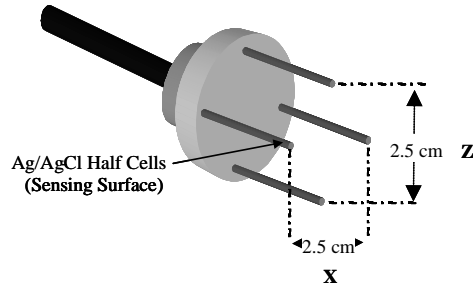
Figure 5-7: Schematic of electric potential sensor used in experiments to measure differential electric potential.

From the four sensors, two differential electric potential values are calculated: (1) the potential differential in the vertical (z-direction) from the top and bottom sensors and (2) the potential differential in the horizontal (x-direction) from the left and right sensors. Differential electric potential values in the electrolyte will experience variations as the amount of anode current changes due to the change in cathode area (i.e. changes in damage).

6 RESULTS

The current values of the anodes are the input to the analysis solution. Symmetry is maintained by forcing the port/starboard anode pairs to have the same current. The current values are manually iterated until the desired value of −850 mV Ag/AgCl reference electrode is achieved at the starboard reference cell. Since the port reference cell is situated slightly aft of the starboard reference cell, its voltage value will be slightly higher, due to being closer to the aft anodes which have higher current than the forward anodes. However, since the target reference cell reading is −850 ± 25 mV both reference cells are within the target range. So the slightly non-symmetric placement of the reference cells is not a problem.

The resulting iteration values for the anodes and reference cells are shown in Table 6−1 for the damage cases considered. For well behaving systems with good initial guesses, a valid solution can be found after only a few iterations. If the target range were narrowed, then more iterations would be needed. Table 6−2 recaps the final values of the anodes and reference cell for the valid solution. Increasing the amount of damage from the baseline damage of 5.7% to 10.7% increases the aft anodes from an input current of 13.35 mA to 21.6 mA and the forward anodes from 6.675 mA to 10.8 mA.

In addition to anode and reference cell values, hull potential plots and off-board electrical potential differential values are of interest.

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Table 6-1: Iterated anode current values and the resulting reference point voltages for various amounts of damage.

| Damage Case	Iteration	Aft Anodes (mA)	Forward Anodes (mA)	Starboard Reference Cell (mV)	Port Reference Cell (mV)
1: Baseline	1	13.6	6.8	-866.73	-882.82
	2	13.3	6.65	-847.59	-863.32
	3	13.4	6.7	-853.97	-869.82
	4	13.35	6.675	-850.78	-866.57
2: Baseline + 2.6%	1	20	10	-964.95	-985.56
	2	18	9	-868.36	-886.90
	3	17.6	8.8	-849.04	-867.17
3: Baseline + 5%	1	20	10	-787.66	-805.81
	2	25	12.5	-985.63	-1008.3
	3	22	11	-867.23	-887.20
	4	21.6	10.8	-851.45	-871.05

Table 6-2: Final anode current values and final reference point voltages for various amounts of damage.

| Damage Case	Aft Anodes (mA)	Forward Anodes (mA)	Starboard Reference Cell (mV)	Port Reference Cell (mV)
1: Baseline	13.35	6.675	-850.78	-866.57
2: Baseline + 2.6%	17.6	8.8	-849.04	-867.17
3: Baseline + 5%	21.6	10.8	-851.45	-871.05

6.1   HULL POTENTIAL PLOTS

The potential profile plots for each damage case are shown in Figure 6–1 to 6–3. The potential profiles are identical outside of the region immediately adjacent to the damage. As the damage increases, there is a change in the potential field on the insulated propeller. With sufficient

resolution of reference cell placement it could be possible to identify both damage extent and location. However, the number of sensors required to perform this identification using only hull potential mapping would be high. Even with advanced multiple anodes, multiple reference cells, and digitally controlled ICCP systems, only gross locations of damage would probably be possible. Detailed evaluation of anodes effects testing where the influence of small groups of anodes on the hull potential profile would provide insight into potential mapping capabilities for identifying damage extent and location. The present model does not have sufficient complexity in the ICCP system to model anode-hull damage interactions captured by sequencing anode input such as occur on a real ship. Therefore anodes effects testing was not modeled with the present geometry.
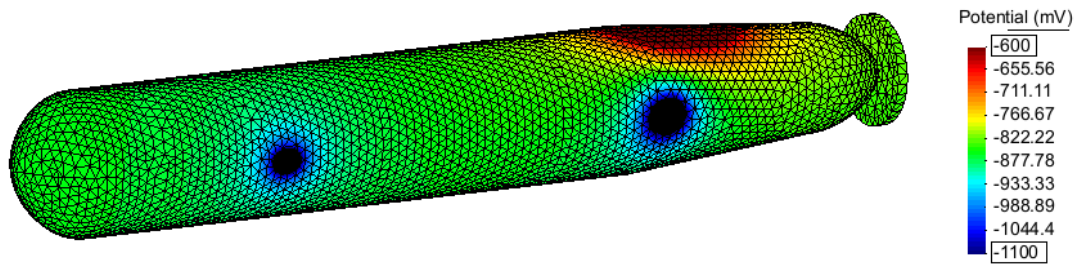
Figure 6-1. Contour plot of on-board hull potential for the baseline 5.7 % damage.
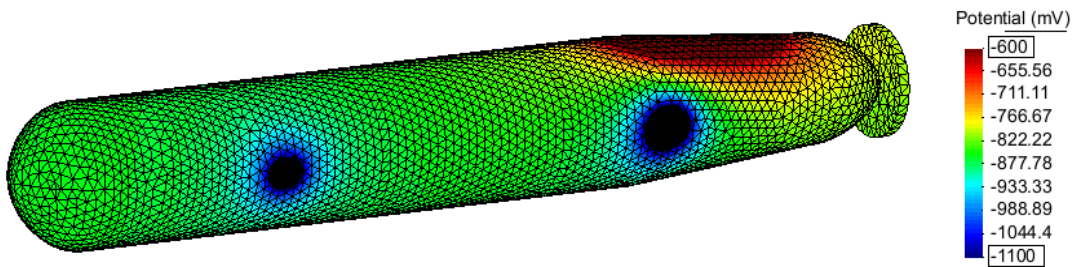
Figure 6-2. Contour plot of on-board hull potential for the baseline plus 2.6% damage.
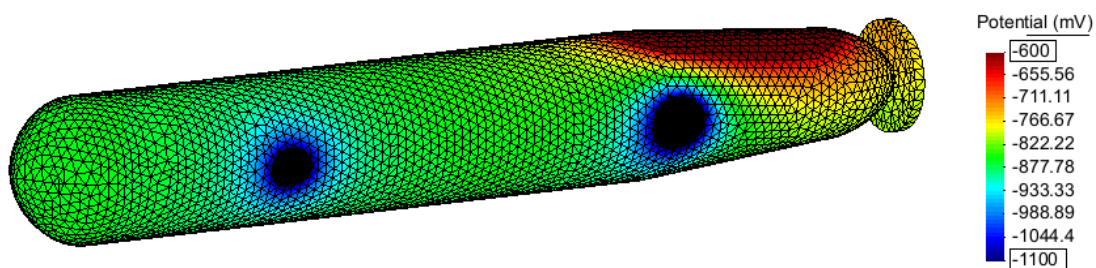

Figure 6-3. Contour plot of on-board hull potential for the baseline plus 5% damage.

6.2 OFF-BOARD PLOTS

The calculated electric potential differentials for the three damage cases are shown in Figure 6–4. A variation in the differential is readily noticeable and measureable. The maximums of potential differential in the horizontal (x-direction) for the three cases are 0.65, 0.88 and 1.11 mV, for the difference damage cases of 5.7%, 8.3% and 10.7% respectively. The minimums of potential differential in the vertical (z-direction) for the three cases are −0.55, −0.82, and −1.12 mV. This indicates that a sensor based tool that uses the variation in differential is feasible. There is the capability to use this type of data from off-board sensors, such as would be found in a range or could be placed on the transit path into port, to build a computational tool to identify at least the magnitude of damage.

For this program, the next step was intended to be determining how small an area of damage is detectable. Computationally, small areas of damage are easy to create. Numerically more precision can be added by using more iterations with a tighter reference cell target range. However, on a range or in the Physical Scale Model (PSM) environment, the smallest area of damage that is detectable would depend upon measurement sensitivities or errors along with the ability to physically create small pieces of bare metal on the PSM model.
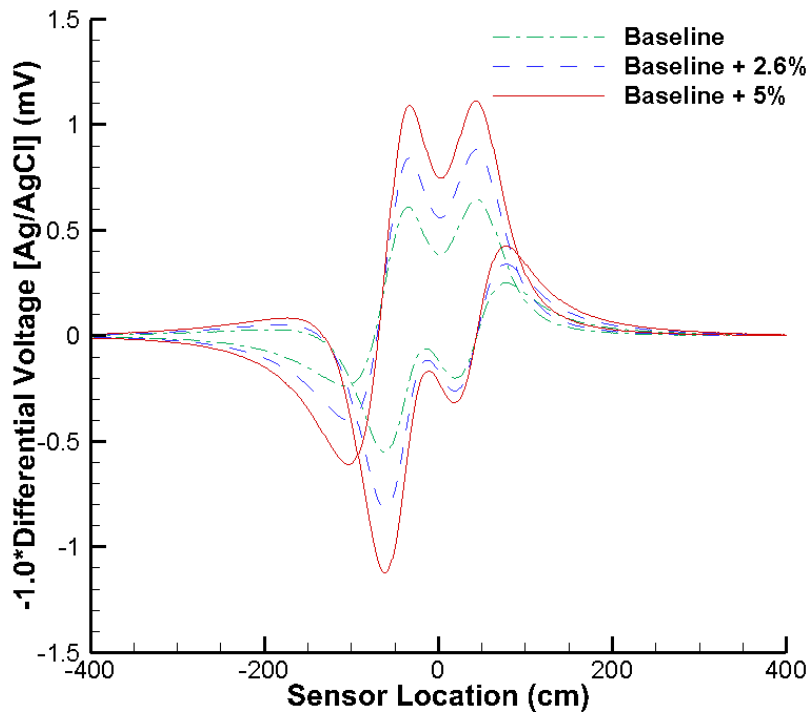
Figure 6-4. Comparison of calculated electric potential differential for various amounts of damage.

7 SUMMARY

The Underwater Hull Analysis Model was planned to be a validated computational tool in its final stage. In this, one of the initial proof of concept steps, the authors were just beginning the validation process. At the moment, it is important to be able to identify the relative magnitude of changes in off-board field characteristics as related to changes in hull damage. It was conceivable that small variations of hull damage will not result in measureable variations in sensor data. This work verifies that small amounts of damage do result in measureable variation in off-board field values. The proof of concept work presented here provides the analyst insight into the relationship between on board damage and off-board field magnitudes. This will assist in the planning for future computational modeling and experimentation.

Later work was planned that would look into the limits of how small an area of damage could be identified using actually sensor sensitivity limits and if spatial location on the hull had an impact on this minimum incremental damage value. At that point, a specific hull geometry would h identified and both computational and experimental work would be completed to validate the damage sensitivity for a specific hull configuration.

8 ACKNOWLEDGEMENTS

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